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PHOSPHORUS REMOVAL FROM DOMESTIC WASTEWATER IN HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND AFTER 8 YEARS OF OPERATION – A CASE STUDY

Agnieszka Karczmarczyk

*Dept of Environmental Improvement, Faculty of Engineering and Environmental Science
Warsaw Agricultural University,
Nowoursynowska 166, 02-787 Warsaw, Poland
E-mail: matczak@alpha.sggw.waw.pl*

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Abstract. Horizontal subsurface flow constructed wetlands can effectively treat high levels of biochemical oxygen demand (BOD) and suspended solids. They are also effective as phosphorus trap but usually for a short time. This phenomenon was observed in the presented case study, an example of subsurface flow reed bed filled with "improved" site soil where it was assumed that the permeability of bed would increase as a result of reed penetration. Fine grained site soil was initially effective trap for phosphorus from wastewater. However, during operation clogging of bed media proceeded and phosphorus sorption capacity used up. In general, the longevity of subsurface flow wetlands as phosphorus sinks depends on the hydraulic load, phosphorus load and the type of the media used in bed construction. To be effective as phosphorus sorbent, substrate should contain high levels of Ca, Al and Fe oxides and possess suitable sorption capacity, quick time of reaction and suitable permeability.

Keywords: on-site wastewater treatment, domestic wastewater, subsurface flow constructed wetland, phosphorus removal

1. Introduction

Constructed wetlands with subsurface flow are widely used throughout the world to treat a wide variety of wastewater like municipal, industrial and agricultural effluents, storm water and landfill leachate. In Poland they operate from early nineties [1]. Mechanisms involved in wastewater treatment in such systems covers a variety of biological, chemical and physical processes [2]. Phosphorus can be removed in constructed wetlands by plant uptake, assimilation by microorganisms and physical-chemical processes involving the wetland soil. Among the physical-chemical processes, sorption by soil and precipitation reactions play an important role. The variety of phosphorus removal efficiency from domestic sewage observed for subsurface flow wetlands in Poland is as high as 1 to 97 % [3–6]. Such big divergences between phosphorus removal efficiency obtained in horizontal subsurface flow systems are the result of different phosphorus and hydraulic loads, retention time, media used for bed construction and how long the system is operated.

In wetland, phosphorus accumulates in plants and sediments until both are saturated [7]. Plants contain only a small amount of the total phosphorus that occurs in wetland, thus the P uptake capacity of macrophytes in treatment wetlands is limited [2]. The amount of phosphorus that can be removed from the system averages from 5 to 20 % of phosphorus stopped in soil-plant system [3, 8–13]. Soil adsorption capacities can be theoretically estimated on the basis of batch and percolation tests [8, 14–16]. However, some factors can influence accumulation process. The longevity of any system will depend on the type of wastewater to be treated and can be limited by the effects of organic matter, suspended solids, and other effluent components on the system's performance [17]. In some cases, leaching of metals responsible for phosphorus binding from bed media was observed [16, 18]. One of mechanisms contributing to phosphorus removal via wetland substrate can be regeneration of P-retention sites. Soils regaining their capacity to adsorb phosphorus when it is added gradually in low concentrations and after drying and wetting cycles

[17]. The other factor influencing potential life of treatment system is permeability of designed bed. Most of constructed wetlands in Poland were constructed with sand, gravel or site soil as a growth medium for the plants [1]. In order to maintain high hydraulic conductivity necessary for subsurface flow, soil materials should not be used [19]. Beds built using soil medium, where it was assumed that the hydraulic conductivity would increase as a result of roots penetration, suffered from surface flow leading to channelling and scouring of the surface. This led to bypassing and hence reduced treatment [20].

Phosphorus removal efficiency in subsurface flow constructed wetlands is in generally initially high but in many cases decreases after some time as the sorption capacity of filter media is used up [21, 22]. Once adsorption and precipitation have become saturated, the wastewater treatment wetlands reach P-storage capacity and no longer function effectively for P removal [19]. Constructed wetlands are effective for phosphorus removal for approximately 5 to 8 years [13]. After becoming saturated they start releasing excessive quantities of phosphate [23]. In generally, wetlands are not particularly effective as phosphorus sink when compared with terrestrial ecosystems [19].

Some authors reported that the overall phosphorus removal efficiency can amount to above 90 % when special media are used. Such materials of natural origin as Light Expanded Clay Aggregate (LECA) [24–27], shale [25, 28], opoka [29, 30], or anthropogenic origin and waste products like fly ash [25], Blast Furnace Slag (BFS) [30, 31]; wollastonite [32], Pulverized Fuel Ash (PFA) [20] and many others were already studied as a potential filter media in constructed wetland systems. To be effective as phosphorus sorbent, substrate should contain high levels of Ca, Al and Fe oxides and possess suitable sorption capacity, quick time of reaction and suitable permeability.

The object of the presented investigation was to monitor the phosphorus removal efficiency in subsurface flow constructed wetland treating domestic wastewater for 8 years. Observed plant is located in central Poland in typical climate conditions, and it is an example of horizontal subsurface flow system based on the Kickuth license, where site soil was used as a substrate for bed construction. The goal of investigation was to determine possible reasons of poor phosphorus removal in system, to avoid made mistakes while the existing system will be modernized and developed.

2. Site description

Wastewater treatment plant in Bolimów commune is operated from February 1995. The treatment system consists of mechanical pre-treatment (screen bars, sand trap and Imhoff tank), reed bed (horizontal subsurface flow constructed wetland), ditch for phosphorus removal and stabilization pond. The schematic view of the system is presented in Fig 1. The construction of the plant was supervised by the Kickuth licence. Domestic wastewater coming from the village and the commune area are treated in the system. At the beginning, almost all sewage come from septic tanks, so they were highly concentrated and had to be diluted. The volume of the sewage treated at the plant averaged 500 m^3 per month. In 1999 sewerage system started to be built, what resulted in the change in quality and quantity of delivered sewage. At the end of the year 2000 all wastewater from the village came to the plant by sewerage system and from the commune area septage was still brought by trucks. The daily flow of wastewater through the system in 2000–2002 varied from 11,2 to 63,5 m^3 d^{-1}, with the average 39,4 m^3 d^{-1}. At the end of 2002 only one from originally planned two horizontal subsurface flow reed beds was under operation. The maximum volume of sewage which can be treated in the bed amounts 80 m^3 d^{-1}. The bed consists of two parallel filters. Filter media used for bed construction in Kickuth licence based systems is a mixture of silty minerals, organic matter and sand or gravel. In the presented case site soil improved where the additions were used as a filtration medium. Bed was planted with *Phragmites*. The reed bed is followed by the ditch for phosphorus removal, filled with iron reach sand. Wastewater was distributed to the sand filter and collected by drainage pipes, till the filter became saturated and had to be removed. Then the wastewater flow through the macrophyte planted pond, which is the last step of wastewater treatment system. The receiver of treated sewage is Rawka river, which together with branches, old riverbeds and few tributaries are a natural reserve and a part of Landscape Park.

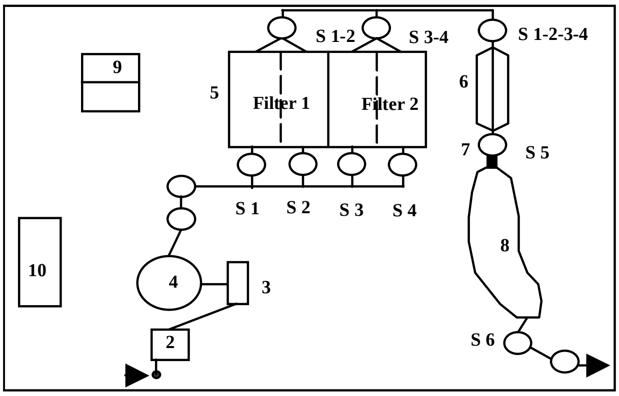

Fig 1. Schematic view of wastewater treatment system in Bolimów: 1 – sewage receiving, 2 – pump station, 3 – screen bars and sand trap, 4 – Imhoff tank, 5 – reed bed, 6 – ditch for P-removal, 7 – flow measurement, 8 – pond, 9 – sludge lagoon, 10 – social building, S – sampling points

3. Methods

From March 1999 to November 2002 wastewater treatment system in Bolimów was periodically monitored. Samples of mechanically pre-treated wastewater, effluent from reed bed, phosphorus removal ditch and pond effluent were analysed for phosphate phosphorus concentration. Sampling points are shown in Fig 1. The inflow and the outflow wastewater samples from the reed bed were collected bimonthly onwards to estimate the percent removal of phosphorus. Commune Office made earlier data (from 1995 to 1998) available. Before analysed, sampled wastewater were filtered through high-density paper filters. Phosphorus concentration was determinate by using colorimetric methods on the SLANDI LF-205 photometer not later than 4 hours after sampling. Phosphates at the range from 0,1 to 2,0 mgPO$_4$ dm^{-3} were measured by molybdate method at 635 nm, and phosphates at the range 3 to 120 mgPO$_4$ dm^{-3} were measured by moly-vanadium method at 480 nm. Average phosphorus reduction at the following stages of wastewater treatment was calculated as follows:

$$\eta = \frac{\overline{C_{wl}} - \overline{C_{wyl}}}{\overline{C_{wl}}},$$

where $\overline{C_{wl}}$, $\overline{C_{wyl}}$ are mean phosphorus concentrations in influent and effluent wastewater, respectively, and showed as a percentage.

4. Results and discussion

The main part of wastewater treatment system in Bolimów is subsurface horizontal flow bed planted with reed. Wastewater is treated there in physical (sedimentation, filtration, adsorption), chemical (precipitation, adsorption, decomposition) and biological (bacterial metabolism, plant adsorption, natural die-off) processes [2]. In constructed wetlands there are several processes by which P may be removed from the wastewater: adsorption onto substratum, precipitation and complexation reactions, plant uptake and biological incorporation into biofilm. Adsorption reactions on the bed media is the most important phosphorus removal pathway [23].

There are only few data available from the operation period of 1995–1998. Single data from Commune Office cannot be used for inference about the treatment efficiency, however, one can say, that phosphorus removal efficiency in reed bed was initially high (Table). From 1999 phosphorus removal efficiency was periodically monitored and results were statistically analysed. As it is shown in Fig 2, phosphorus removal in reed bed wasn't effective. Moreover, release of phosphorus from the bed occurred

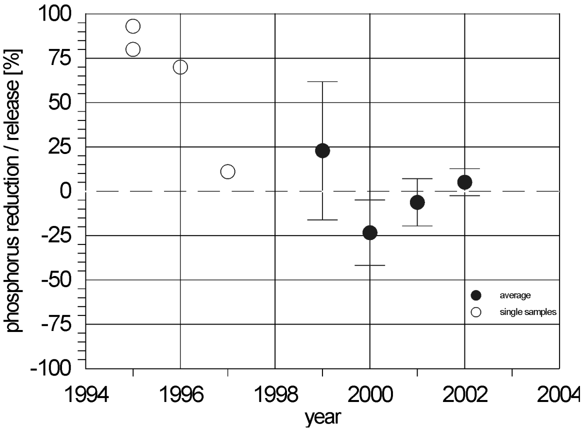

Fig 2. Phosphorus reduction and release in reed bed during 8 years of operation

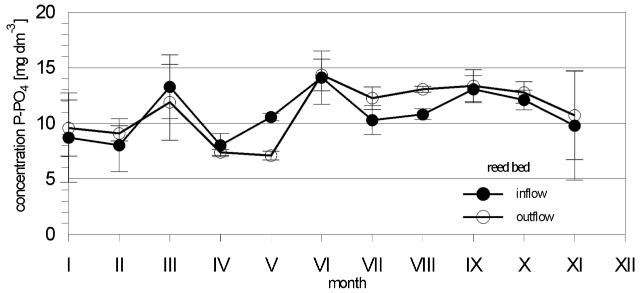

Fig 3. Phosphorus removal efficiency during the year based on average

Fig 3 represents monthly average treatment performance of the reed bed for influent and effluent concentration of P-PO$_4$. Phosphorus removal efficiency during the year shows seasonal changes. Reduction of phosphorus in the bed occurred only from March to May. Such a phenomenon suggests that the plant uptake is supposed to be the main mechanism of phosphorus removal in the bed. Even through vegetation, detritus, fauna and microorganisms are an important sink for phosphorus in the short term, substrate is the main sink for P in the long term [31]. In general, phosphorus in constructed wetlands accumulates in plants and medium until both are saturated. Intensity of biogens bioaccumulation depends on plant development phase, age of the plant and availability of biogens [33]. Plant biomass takes up nutrients in spring during its intensive growth. Above ground part of the plants start to release phosphorus in June and last to the end of September [34]. The maximum P that plants may remove from a

Total phosphorus reduction in the reed bed, P-removal ditch and pond in 1995–1998 (based on Commune Office data)

Sampling day Treatment stage	23 05 1995	12 09 1995	08 07 1996	09 04 1997	14 05 1998
Reed bed in/out (mgP dm^{-3}) reduction (%)	25,0 / 1,65 93	19,7 / 3,94 80	38,4 / 11,5 70	27,5 / 24,6 11	12,2 / 5,78* 53*
P-removal ditch and the pond in/out (mgP dm^{-3}) reduction (%)	n. d.	n. d.	11,5 / 9,93 14	24,6 / 18,6 24	n. d.

*including phosphorus reduction in phosphorus removal ditch
n.d. – no data available

sewage effluent is 0,3 t ha^{-1} y^{-1} but most is in the roots and dead material [7]. Besides intensive plant uptake, considerable bed aeration by macrophytes can limit release of phosphorus from sediments in spring. In anaerobic conditions phosphorus in wetland sediments may return into solution from its combination with organic matter [18, 35].

There can be two possible reasons of inactivation of the bed phosphorus sorption ability. One is saturation of bed substrate, the second is poor bed permeability. Substrate saturation often proceeds when the media with very low P sorption capacity, eg gravels, are used. In the presented case improved site soils were used. Fine-grained media usually have large P sorption capacity, however, its filtration ability is rather weak [19, 27]. Fully developed reed bed built with soil would have a hydraulic conductivity of about 260 m d^{-1}. Presented plant was built using soil medium where it was assumed that the permeability would increase as a result of root penetration of the bed. Unfortunately, roots and rhizomes of aquatic plants do not open up hydraulic pathways in root zone systems, as it was previously proposed by Kickuth, and they fully occupy closed channels formed as they push their way through the soil [36]. As a result, some of these beds suffered from surface flow leading to channelling and scouring of the surface which in the areas of the beds being starved of water. Although the average flow rate 39,4 m^3 d^{-1} delivered to the wetland, being approximately 50 % of the maximum flow, surface flow characteristically occurred over the wetland during the monitoring period. Phosphorus removal in subsurface flow wetland is strongly dependent on the medium sorption capacity and permeability. Poor filtration ability of substrate results in surface flow and makes phosphorus sorption impossible as a contact between wastewater and substrate is limited.

5. Conclusions

Initially high phosphorus removal in subsurface horizontal flow reed bed in Bolimów wastewater treatment plant became insufficient after four-five years of operation. Only within spring period reduction of phosphorus was observed and for the rest of the year phosphorus release occurred. As possible reasons of this phenomenon P-saturation of bed substrate and/or low bed permeability was recognized. By using sands, gravel stones or site soils for bed construction it is not possible to achieve high and sustainable phosphorus removal in subsurface flow wetlands. Phosphorus removal in such systems may be best done in a specialized treatment stage either before or after the reed bed or by using an alternative media in bed construction.

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FOSFORO ŠALINIMAS IŠ BUITINIŲ NUOTEKŲ HORIZONTALIOSIOS POPAVIRŠINĖS TĖKMĖS DIRBTINIAME BIOLOGINIAME TVENKINYJE

A. Karczmarczyk

Santrauka

Dirbtinai įrengti horizontaliosios popaviršinės tėkmės tvenkiniai efektyviai valo didelio BDS (biologinio deguonies sunaudojimo) bei suspenduotųjų kietųjų medžiagų labai užterštas nuotekas. Jie trumpam taip pat efektyvūs kaip fosforo absorbentai. Šis reiškinys tirtas stebint popaviršinę tėkmę vandens augmenijos priveistame pagerintame grunte. Buvo manoma, kad vagos pralaidumas dėl vandens augmenijos padidės. Smulkiagrūdis gruntas iš pradžių fosforą iš nuotekų sorbavo efektyviai. Tačiau proceso metu dėl teršalų pertekliaus tvenkinio sorbcinė geba baigėsi. Apibendrinant, ilgalaikė biologinių tvenkinių fosforo sorbcijos geba priklauso nuo jų hidraulinės apkrovos, fosforo kiekio ir įkrovos, naudojamos įrengiant tvenkinį, tipo. Kad fosforo sorbentas būtų efektyvus, substratas turi būti atitinkamos pradinės sorbcinės talpos ir laidumo. Jame turi būti didelis kiekis Ca, Al bei Fe oksidų.

Raktažodžiai: vietinis nuotekų valymas, buitinės nuotekos, popaviršinės tėkmės dirbtiniai biologiniai tvenkiniai, fosforo šalinimas.

ОЧИСТКА ФОСФОРА ИЗ БЫТОВЫХ СТОКОВ В ИСКУССТВЕННЫХ ПРУДАХ С ГОРИЗОНТАЛЬНЫМ МЕЖСЛОЙНЫМ ТЕЧЕНИЕМ

А. Карчмарчик

Резюме

Искусственно созданные пруды с горизонтальным межслойным течением могут эффективно очищать стоки с большим биологическим потреблением кислорода (БПК) и осадочными веществами.

Пруды также эффективно, однако в течение короткого времени удаляют фосфор. Это явление наблюдалось в межслойном течении в улучшенном грунте, засаженном водяными растениями. Предполагается, что пропускная способность пруда увеличивается за счет водной растительности. Мелкозернистый грунт вначале был эффективным сорбентом фосфора из сточных вод. Однако в процессе эксплуатации пруда из-за переизбытка загрязнителей сорбционная способность удалять фосфор утрачивается. Обобщая, можно констатировать, что долговременная способность прудов удалять фосфор в межслойном течении зависит от гидравлической нагрузки, количества фосфора и типа загрузки, используемой в конструкции пруда.

Чтобы субстрат был эффективным сорбентом фосфора, он должен содержать как можно больше оксидов Ca, Al и Fe и обладать достаточной сорбционной способностью, кратковременной реакцией и соответствующей пропускаемостью.

Ключевые слова: местные очистительные сооружения, бытовые стоки, искусственные пруды с межслойным течением, очистка фосфора.